Ultrasonic Removal of Near Wellbore Damage Caused by Fines and Mud Solids

The technology described is applicable to the treatment and removal of near wellbore formation damage.

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ABSTRACT

Laboratory experiments were conducted to investigate the feasibility of using ultrasonic energy to reduce formation damage caused by fines and mud solids. Cores were damaged with drilling muds in a dynamic filtration cell. Damage due to fines migration was simulated using fresh water injection. The damaged cores were then treated with ultrasonic energy at various frequencies and intensities. Experiments were conducted with fully brine saturated cores and cores partially saturated with decane. The permeability was monitored as a function of ultrasonic treatment time, during backflow, for three different sections of each core. The permeability increase, the depth of treatment and the ultrasonic energy requirements were investigated for both sandstone and limestone cores. The results showed that the permeability increased by a factor of 3 to 7 after ultrasonic treatment for cores that were damaged by mud solids and fines migration. Treatment was successful for frequencies of approximately 20-80 KHz and acoustic intensities of approximately 20-250 W/m^2. For these wavefield parameters, the effective depth of treatment for reducing fines damage was approximately 2.5 inches. Damage caused by mud infiltration penetrated only the first 2.5 inches of the cores and, thus, ultrasonic treatment had no effect on deeper sections.

INTRODUCTION

Near-wellbore formation damage can cause devastating effects on oil production rates due to severe reductions in effective permeability. As a result, the search for effective methods to treat wellbore damage is of great concern in oil and gas production. The dominant causes of near-wellbore damage vary from one well to another, but damage associated with the transport of colloidal solids into or out of the wellbore is a key mechanism. Previous research indicates that, during drilling, mud particles invade the formation and reduce its permeability by blocking constrictions in the flow channels[1]. Prevention of such damage requires extensive and expensive pretreatment of fluids that are used for completion, fracturing, injection and perforation. Even though these preventive measures are effective for limiting the extent of formation damage caused by injected fluids, it fails to address the problems that arise during post-completion production. Wellbore damage arising from the plugging of pores due to fines migration during production sometimes cannot be addressed by the same preventive methods because of the difficulties involved in preventing fresh water contact on water sensitive formations. The success of current methods of treating damage is variable and depends on the condition of the well to be treated. For example, acidizing, in some instances, can be damaging to the formation, mainly due to the plugging of pores by loose fines generated during acidizing, precipitation of iron reaction products, and organic sludges. Acidizing can also be an expensive and difficult operation in horizontal wells, where large sections of open hole need to be treated. Large acid volumes may be required in such cases. There are also significant environmental concerns about the disposal of the spent acid.

The use of ultrasonics to remove wellbore damage due to mud solids invasion or fines migration in the field may be implemented as a wireline deployable tool, which may be used in conjunction with or as an alternative to acidizing.

So far no widely accepted method has been devised to remedy the harmful after effects of fines migration. The downhole application of ultrasonic energy for cleaning formation damage has been studied in the past. A comprehensive review of research performed in this area, primarily by U.S. and Russian scientists, was presented by Beresnev and Johnson[2]. Most in-situ field tests of ultrasonic cleaning have yielded limited success because little is known about the physical mechanisms of wave interaction with particles trapped in porous media, and the optimum wavefield parameters required to liberate these particles are poorly defined. As a result, ultrasonic cleaning has received little consideration as an effective and reliable method for wellbore cleanup and has not yet been developed for routine field applications.

The beneficial effect of ultrasonic cleaning has been put to use in various applications for quite some time. The most important physical mechanisms that have been identified to explain the cleaning effect of ultrasound are acoustic streaming and acoustic cavitation. Acoustic cavitation is the formation of gas- or vapor-filled cavities in fluids due to acoustic tension generated by applying sinusoidal sound waves in the fluid. These cavities expand during the dilitational phase of the acoustic cycle and implode violently during the compressional phase, producing localized spots of high temperature and pressure[3]. Due to the violent collapse of the oscillating bubbles, cavitation has been used successfully in numerous industrial applications for removing particulate contamination from hard surfaces. It has been shown in numerous studies that cavitation in water is most effectively generated at frequencies below 1 MHz and is controlled partially by the size of particle impurities in the fluid that act as nucleation sites for bubble growth[4,5]. Cavitation is suppressed at high fluid pressures but is promoted by the presence of dissolved gas and particulate contaminants in the fluid.

Acoustic streaming is characterized by steady rotational flow occurring as a result of the interaction of acoustic waves with physical inhomogeneities in a fluid, such as smooth boundaries and solid particles. Fluid agitation caused by acoustic streaming is not as violent as that caused by cavitation, but streaming is very effective for liberating particles attached to surfaces[6]. The streaming mechanism is utilized in the semiconductor industry to clean contaminant particles from substrate wafers[7,8,9]. Streaming can be induced at much lower acoustic intensities and over a broader range of frequencies than required to produce cavitation.

The main objective of our study was to quantify the physical conditions under which ultrasonic energy can be used for removal of near wellbore damage, and to identify the dominant physical mechanism, acoustic cavitation or streaming, responsible for the cleaning effect. Experiments were conducted with laboratory core samples to evaluate the extent of cleaning possible in the cases of damage induced by mud solids infiltration, and in-situ fines

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migration caused by fresh water injection. The frequencies and intensities of ultrasonic excitation used covered the appropriate ranges for producing both cavitation and streaming.

EXPERIMENTAL SETUP

The main components of the experimental setup used in this study are shown schematically in Fig.1. The circulation system includes a positive displacement pump, used to circulate fluid from a reservoir, through a series of dampeners, across the face of the core, and then back to the reservoir. The pump rate can be adjusted from 0 to 2 gal/min. The circulating pressure can be controlled by a shear valve. The damping system consists of a pulsation dampener and two air-charged accumulators used in series designed to minimize pressure fluctuations.

The core holder, designed at the University of Texas at Austin, is similar to the standard Hassler-sleeve coreholder, and has some extended capabilities. The core holder is specially designed to allow fluid to be circulated across the face of the core. It can hold cores of 1" diameter, with a length of 3 to 12 inches, at a confining pressure of 900 psi. The confining pressure is applied to hydraulic oil surrounding the rubber sleeve. There are four pressure ports along the length of the coreholder. The permeabilities of three adjacent sections of the core (2.5", 2" and 3") can be monitored by measuring the pressure drop across each section. The pressure measurements are recorded automatically, using a digital data recorder. A removable fitting at one end of the core holder was modified to accommodate an ultrasonic source transducer while maintaining the fluid seal of the core holder. When the core holder is placed in the vertical position it is also possible to sonicate the core using a high power acoustic horn. The plug at the opposite end accommodates a calibrated accelerometer which is attached to the face of the core sample for measuring the acoustic intensity of the ultrasonic wavefield. The design of the coreholder enables the monitoring of fluid flow and permeability at ambient pressure while maintaining the confining pressure on the core. The two-phase reverse injection system consists of two constant-flow-rate pumps. One is used for pumping oil and the other is used for pumping brine. The setup also has facilities for pumping oil and brine simultaneously. The flowrate is monitored using the fluid sampler.

Two types of ultrasonic sources were used to sonicate the damaged core samples. The first is a low-power piezoelectric transducer driven by a signal generator and power amplifier. This transducer can be driven at frequencies of approximately 10-100 KHz. The other source used is a high-power acoustic horn that operates at a fixed frequency of 20 KHz. The horn itself is a tapered piece of solid steel to which a piezoelectric driver is attached at the larger end. The power amplification is related to the ratio of the cross-sectional areas of the two ends of the tapered horn. This system can output up to 250 W of acoustic power into the fluid in which the horn tip is immersed. The horn will generate strong cavitation in the fluid for power settings as low as approximately 10 W.

PROCEDURE

The procedure for performing the mud damage experiments is as follows. A core sample (8" long, 1" dia, Berea sandstone) is dried and placed inside the coreholder at a confining pressure of 900 psi. The core is evacuated over a period of 12hrs, to a vacuum of 30mm of Hg. The core is then saturated with a 3% solution of NaCl. The permeability of the core to brine, across three different sections is determined by flowing brine at a constant flowrate and obtaining the pressure drops. The core is damaged by circulating mud (4% bentonite, 2% NaCl) across the face of the core at a differential pressure of 100 psi across the core, for a duration of 10hrs. The extent of damage is monitored by taking continuous permeability measurements across the three sections. The next step is to backflow the core using brine. This results in removal of the external mud cake and an increase in permeability. The backflow is continued up to the point where no further increase in permeability is observed. The core is subjected to ultrasonic energy using first the low-power piezoelectric transducer and then the high-power acoustic horn. The sources were coupled to the core samples by either placing them in direct contact with the rock or by transmitting through a 1 to 2 cm gap of brine solution. The duration of sonication with the horn was restricted to 3 min. pulses, separated by suitable intervals to prevent overheating the tool. Brine is backflowed during sonication and the permeability is measured continuously throughout the treatment process. Estimates of acoustic intensity for the ultrasonic waves passing through the core were obtained from calibrated accelerometer measurements made at the core face farthest from the source. The following formula was used to calculate acoustic intensity (I), given the measured particle acceleration (a_{rms}), the estimated density of the sample (r), the frequency (f), and the acoustic velocity (c), which was measured using pulse transmission delay techniques.

$$I = \rho \, c \, a_{rms}^2 / (2\pi f)^2$$

Additional experiments involved the same steps described above, except that the duration of sonication was extended by increasing the number of pulses, and by varying the flow rate of the brine and the power input to the acoustic horn during sonication. Also, to test the influence of oil saturation, an experiment was performed where the core was reduced to irreducible water saturation, Swirr, by flowing decane. The permeability to decane was obtained. The core was sonicated in the same manner as the brine saturated core. The fractional flow of brine through the core was varied during sonication, to obtain a fractional flow curve. Another experiment was carried out on an Indiana limestone core (6" long, 1" dia), at irreducible water saturation.

The fines damage experiments were conducted using the same equipment as used for the mud damage experiments. However, the circulation system used to flow mud across the face of the core was not used. The experimental procedure is as follows. The core is first evacuated and saturated with 3% NaCl solution. Its initial permeability to brine across the three sections is then measured. Fresh water is then injected into the core while monitoring the permeability to get an estimate of the extent of damage. Next, the core is backflowed with brine until no further increase in permeability is observed. Finally, the core is sonicated and as in the mud damage experiment, acoustic intensity measurements are made while sonicating, and permeability values are obtained for all the three sections.

Two experiments are discussed here on fresh water damage removal. The first experiment followed the above procedure. In the second experiment, the duration of sonication was extended while varying the acoustic frequency and power level as well as the fluid flow rate.

RESULTS AND DISCUSSION

Mud Damage Removal in Brine-Saturated Berea Sandstone

In all following figures, the y-axis represents the ratio of the damaged permeability, Kd, to the original undamaged permeability, Kix, where 'x' is the index for core sections 1, 2 and 3. The x-axis represents experimental time. The damage induced by mud circulation was similar in all the experiments, with the permeability of the first section dropping dramatically and the other sections not being affected significantly. Fig.2 shows the extent of mud damage inflicted in the three sections. Backflowing the core improved the permeability of the first section largely due to removal of the external mud cake. Low power sonication resulted in an increase in permeability for section 1, while the deeper sections were not affected at all (Fig.3). High-power sonication with the acoustic horn was carried out at different power levels and flowrates (Fig.4). Continued sonication did not result in an increase in permeability at the lower flowrate of 1 cc/min. A further increase in permeability was observed after the flowrate was increased to 5 cc/min. Application of ultrasonic energy resulted in an increase in permeability by a factor of 4 (from 0.07 to 0.32). The fact that most of the improvement was brought about by the horn shows that acoustic intensity is an important factor in ultrasonic cleaning effectiveness.

Mud Damage Removal in Berea Sandstone at Swr

For samples at Swirr, the extent of damage inflicted on the core through mud circulation followed by backflow (Fig.5) was the same as for brine-saturated cores. Sonication with the acoustic horn resulted in an increase in permeability by a factor of 2.25 (Fig.6), which is smaller than observed for the brine-saturated case. This shows that the ultrasonic cleaning is affected by the fluid phases that the core is saturated with.

Mud Damage Removal in Limestone

For an Indiana limestone core at Swirr, the extent of damage inflicted on the core due to mud circulation was smaller than that for the Berea sandstone by a factor of 10, although the duration of mud circulation was the same. After backflowing with decane, the cores were sonicated with the acoustic horn. Fig.8 shows that the permeability in section 1 increased by a factor of 1.5 as result of sonication. Thus, ultrasonic cleaning is effective in rocks other than Berea sandstone, although the extent of cleaning may depend on the rock type and its physical properties.

Fines Damage Removal in Berea Sandstone

Fig. 9 shows that fresh-water damage to a Berea sandstone core is uniform over all the sections of the core, as opposed to mud damage, which affected only section 1 significantly. Backflow with brine resulted in an increase in permeability in all the three sections by the same factor. Subsequent sonication with the acoustic horn showed an increase in permeability by a factor of 7. The second and third section were not affected at all by sonication.

Other experiments were carried out for fines damage removal, (results not shown here but are available in Ref.10). The low power acoustic source did not show any effect on the damaged core in all the three sections. Sonication was carried out at different power levels with the acoustic horn, at different flowrates after damaging the core and backflowing it with brine. This resulted in an improvement in permeability by a factor of 3 for section 1. No further increase in permeability was observed at this point. Subsequent sonication was carried out under static conditions, with no flow of brine through the core at the time of sonication. Flow was resumed after each pulse until the permeability stabilized. An additional increase in permeability by a factor of 2 was observed after this second treatment, yielding a cumulative increase by a factor 6 for both treatments.

A possible explanation of these observations is as follows. The acoustic source increases the permeability of the damaged rock by dislodging particles that are blocking the pore throats, into the pore bodies. The absence of any force in the form of fluid flow from the opposing direction allows the sonic energy to remove these particles. Once the flow is re-established, a portion of the fines become reattached to the pore walls, while another portion is flushed out of the pore spaces and into the effluent. This results in an increase in permeability. Samples of the effluent collected from the core holder outlet contained large amounts of suspended fines. This could explain the success of sonication under static conditions accompanied by subsequent backflow. Once again, sections 2 and 3 did not show any increase in permeability.

Measurements using the calibrated accelerometer gave estimated intensities of 3.7 W/m^2 for the low-power source and 62.5 W/m^2 for the acoustic horn operating at 80 W output. This is equivalent to power radiation levels of 7.5×10^{-3}W and 0.127W, respectively, at the end of the core furthest from the source. Thus, there is a loss in acoustic intensity by a factor of approximately 2000 over an 8" long Berea sandstone. This could be the reason for the lack of any appreciable effect of ultrasonics further from the source. The severe power loss is due to a combination of inefficient source coupling to the core and inelastic wave attenuation through the rock. The natural attenuation cannot be mitigated because it is a material property of the rock. Thus, more efficient source coupling is the only way to significantly reduce the source power requirements for achieving effective cleaning.

Given the relatively low acoustic intensities used in the sonication treatments, it is most likely that acoustic streaming is the dominant mechanism responsible for removing particles from within the pore spaces. Cavitation is probably restricted to the near surface region of the core face closest to the source, and could thus play an important role in removing mud particles from the in the first centimeter of the core. Since fines migration produces uniform damage throughout the core, cavitation probably plays little or no role in the cleaning of fresh-water damage.

CONCLUSIONS

This laboratory study suggests that application of ultrasonic energy is capable of partially removing wellbore damage arising from the invasion of mud particles. The treatment is effective in both water phase as well as oil phase. Both limestone and sandstone formations may be treated for mud particle invasion by this method. The effectiveness of sonication depends on the power, the flowrate and the duration of sonication.

The problem of fines damage in reservoirs can also be addressed by ultrasonic treatment. Increases in permeability by as much as a factor of 6 was observed in these experiments. The extent of damage removal depends on the power of the source, and on the coupling efficiency between the source and the sample. The effectiveness of the treatment is enhanced if carried out under static conditions, followed by backflushing.

It is most likely that acoustic streaming is the dominant mechanism for cleaning both mud and fines damage, although cavitation may contribute to the removal of near-surface particles in the mud damage case.

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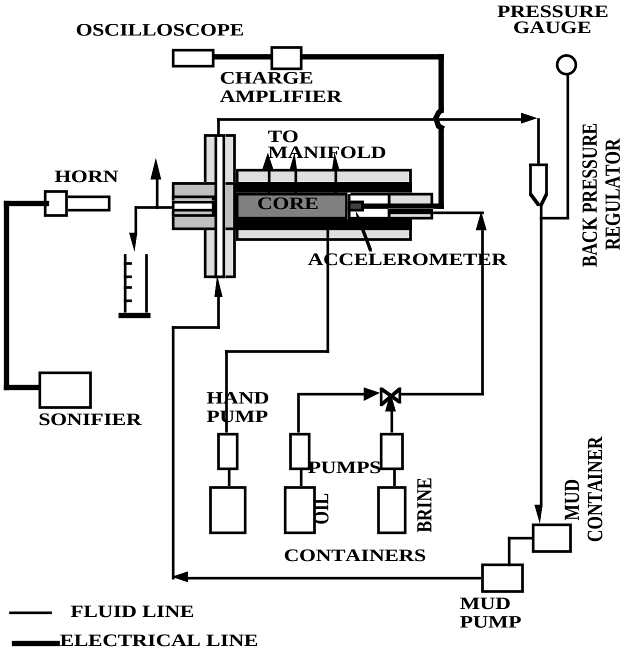

Fig.1 Schematic of the experimental setup

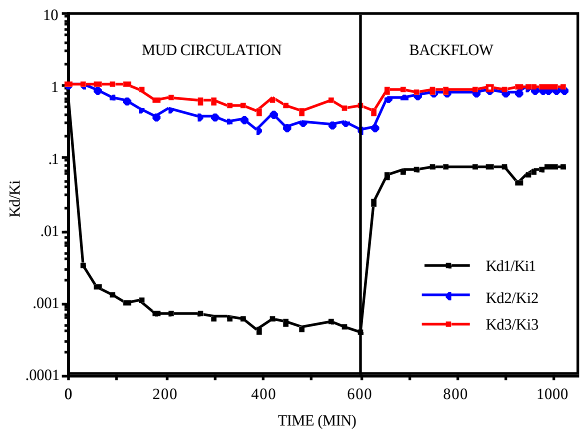

Fig.2 Formation damage due to drilling mud in brine saturated Berea sandstone

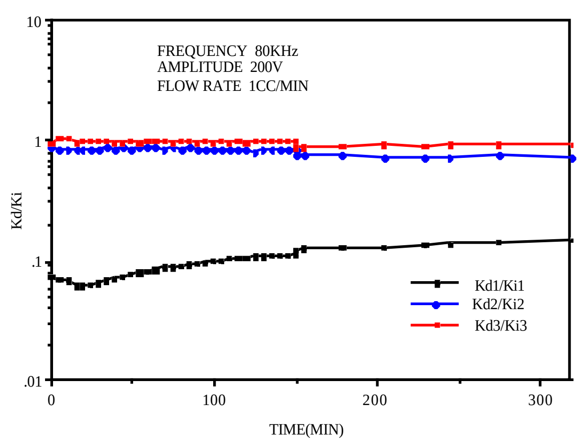

Fig.3 Acoustic cleaning of core damaged by drilling mud (low power acoustic source)

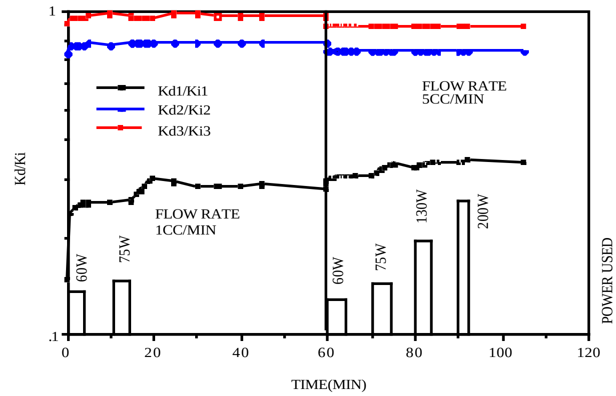

Fig.4 Acoustic cleaning of core damaged by drilling mud (acoustic horn)

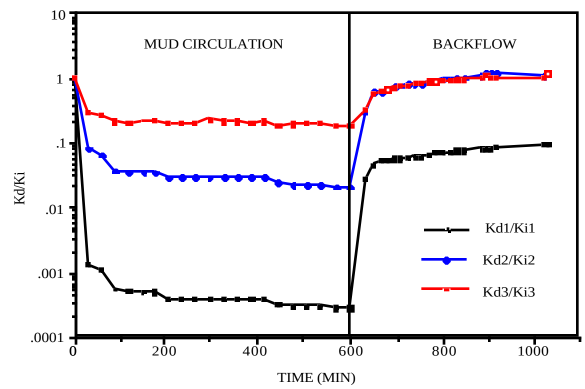

Fig.5 Formation damage due to drilling mud in Berea sandstone at irreducible water saturation

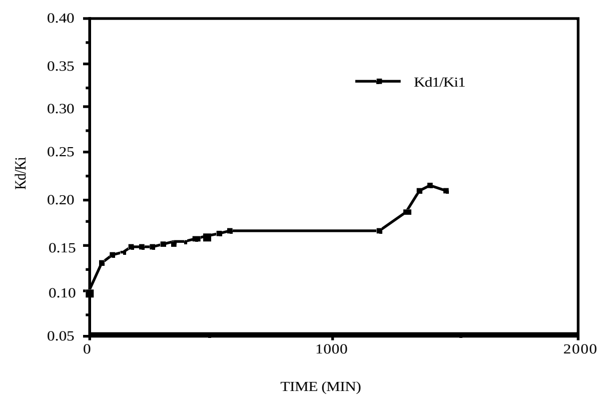

Fig.6 Acoustic cleaning of core damaged by drilling mud (acoustic horn)

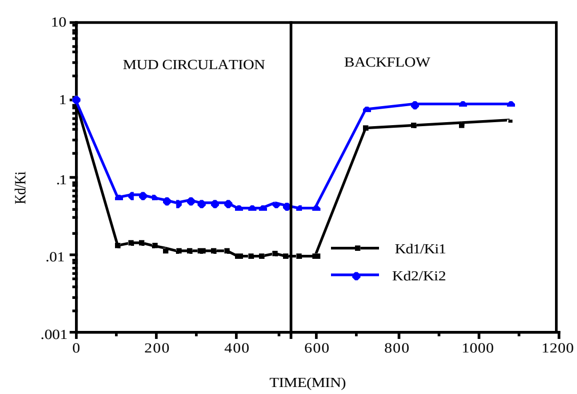

Fig.7 Formation damage due to drilling mud in Indiana limestone

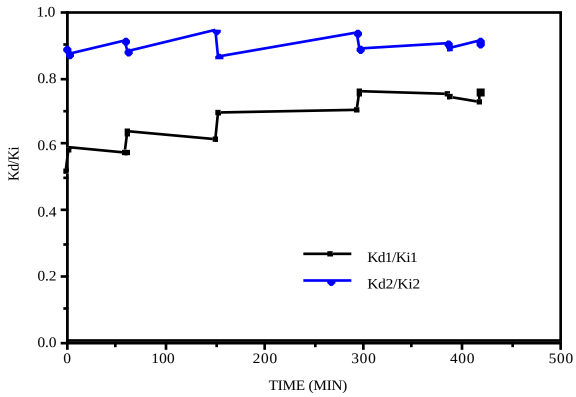

Fig.8 Acoustic cleaning of core damaged by drilling mud (acoustic horn)

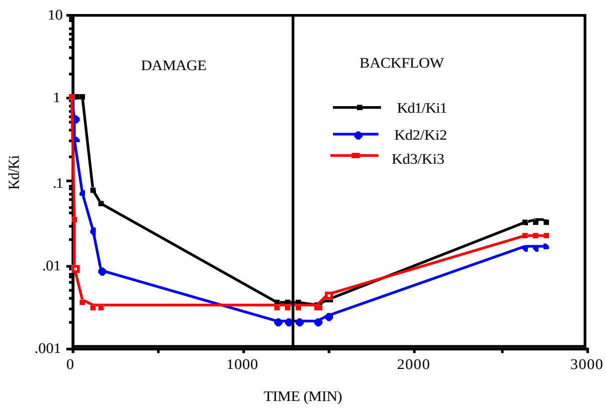

Fig.9 Formation damage due to fresh water injection in brine saturated Berea sandstone

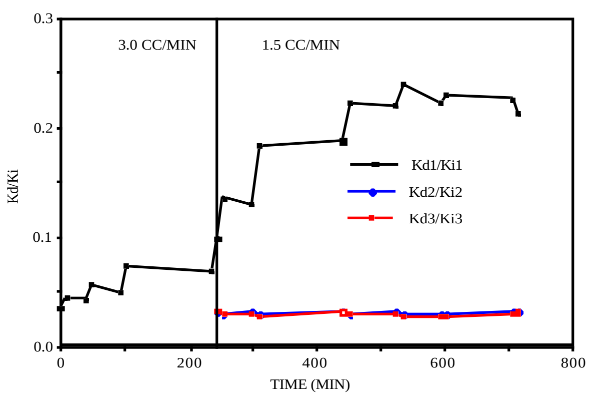

Fig.10 Acoustic cleaning of core damaged by fresh water injection (acoustic horn)